AN ANALYSIS OF PILOTS' PERFORMANCES IN MULTI-ENGINE AIRCRAFT (R5D)

Analysis of data from
NAVAL MEDICAL RESEARCH INSTITUTE
BuMed Project X-651

Contract N6ori-151, Task Order No. 1
Project No. 20-0-1

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The basic data for this report were taken from records of a field study conducted by the Naval Medical Research Institute under BuMed Project X-651, "Human Engineering in Aircraft Design".

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I. SUMMARY AND CONCLUSIONS

1. In this study the principles of job analysis and of time and motion are applied to the task of flying a multi-engine aircraft, the R5D (the Navy equivalent of the C-54 or DC-4). Cinematographic records and voice recordings were made by two aviation psychologists during scheduled flights in July and August of 1946. These records are analyzed to determine if the methods used ~~currently~~ in industry are productive and practicable when applied to piloting.

2. The cockpit of the R5D is divided into seven general work areas as a basis for analyzing motion pathways. Each control is described, with detailed consideration given to its location and to the extent of pilot's arm and body movement required for operation.

3. Photographic records of various phases of the flights were subjected to frame by frame study and process charts are presented for the pilot's and co-pilot's performances with the time required for each operation indicated.

4. An analysis was made of the voice recordings and charts are presented showing the frequency of use of controls by pilot and co-pilot during take-off, cruise, and landing.

5. The investigations were not designed to accumulate any considerable amount of quantitative data, but rather to test the applicability of this method of study. However, the data obtained are sufficient to suggest the following conclusions:

a. The task of piloting can be subjected to time and motion analysis similar to that used in industry. By the application of such methods much can be learned about the pilot's operation of the various controls and instruments.

b. Moving pictures and voice recordings give permanent, objective, and descriptive records which can be studied in the laboratory for establishing the motion pathways and the times required to operate the controls.

Moving pictures are useful also in studying the coordination of duties of pilot and co-pilot.

c. Check-off procedures can be improved and simplified by systematizing and standardizing the sequence of operations.

d. There is an unduly heavy work load on the right hand of the pilot and on the left hand of the co-pilot. This may create a problem in the transfer of skills, where the co-pilot, who has been using primarily his left hand, is moved to the pilot's position.

e. There is an unequal division of tasks between pilot and co-pilot during certain phases of flight, and considerable variation between pilots.

f. The maximum arm reach of a group of Navy pilots is given and compared with the distance from normal flight position to various points in the cockpit. It was found that the pilot is often required to operate controls located as much as 15 inches beyond his finger-tip reach. Such operations require considerable trunk movement, with resulting bodily and visual displacement from the normal flight position.

g. The stimuli or cues which elicit the pilot's responses in operating the controls are identified as visual, auditory, kinesthetic, and temporal. Of these the visual and temporal are found to be relied upon most frequently.

6. Recommendations are made for extending the investigation, and improvements in the recording equipment are suggested.

7. The implications of such an extended investigation for design of cockpits and training of pilots are discussed.

II. ACKNOWLEDGMENTS

This investigation was authorized by the Bureau of Medicine and Surgery as part of project X-651, and was carried out by representatives of the Naval Medical Research Institute. Upon demobilization of the officers assigned to the project, support for completion of the investigation was given by the Special Devices Division of the Office of Naval Research through a contract existing with the Bio-Mechanics Division of the Psychological Corporation. The author, who is now a staff member of the Bio-Mechanics Division of the Psychological Corporation, was one of the officers originally assigned to the project.

Grateful acknowledgment is made to Commander Barry G. King, H(S)USNR, for his assistance in the organization of the project, and to Lieutenant Commander Irving A. Fosberg, H(S)USNR, for his aid in planning and carrying out the field study.

The writer wishes to express his sincere gratitude and indebtedness to the many squadron commanding officers, the pilots, the flight surgeons and all personnel of the Naval Air Transport Service whose interest and enthusiastic cooperation made this work possible.

Acknowledgment is due and gratefully accorded D. L. Chadwick, (CAP)USN, for his assistance in the analysis of the data and interpretation of the results.

III. PURPOSE AND SCOPE OF INVESTIGATION

The project was designed to permit observation and recording of cockpit procedures, flight patterns, pilot reactions, and operational flight problems. The scope of the present report includes a discussion of the application of time and motion methods and job analysis technics to the task of piloting, analysis of data concerning the pilot's use of the various instruments and controls, and the implications of the findings.

The idea of subjecting the pilot's tasks to a job analysis, with its related principles of time and motion, is not new in the field of aviation research. For many years specialists in this field have desired more definite information about the performances required in piloting aircraft.

As pointed out by McFarland (1), there is a need for "an investigation of the nature of (the pilot's) tasks, the surroundings in which he works, the location of instruments and controls and the way in which he performs his duties". McFarland recommends "that time and motion studies be made in the preliminary design of air transports to determine the precise duties of each crew member and the time available for carrying them out during the most important maneuvers such as take-off and landing". A search of the literature reveals that only a very limited amount of work has been done in applying time and motion methods to the task of piloting.

Harlan and Wood (2) made a preliminary but detailed study of all the co-pilot's movements during and after a landing. They recorded these actions by means of a motion picture camera. A subsequent analysis, which was concerned with only the number rather than the type of movements, showed that these vary from one every 1.8 seconds to one every 3.0 seconds, depending upon the position of the plane in the various zones of the standard landing pattern.

R. S. Johnson (3) of United Air Lines developed an effective method of inte-

grating the various duties on the flight deck. His procedure consisted of arranging the operations performed during each phase of flight in the order which permitted the simplest and smoothest paths of movement, with a division of the tasks between the two flight officers. These flight scripts were then placed on an instrument termed the "flight coordinator" and installed permanently on the control pedestal so that pilot and co-pilot could follow a standard routine of operation. By so systematizing the flight duties, Johnson found that he could effectively reduce the time required to carry out the performances during various phases of flight. For example the time needed for engine run-up was shortened from 9 minutes to an average of 2 1/2 minutes. It is evident that reductions of time and effort may be effected by the introduction of a systematic sequence of operations.

If only the mechanical aspects of the pilot's task are considered, then an incomplete picture will be obtained. While it is not the purpose of this paper to consider the human factor in terms of physiological changes, such studies will have to be made. A preliminary and interesting investigation of this problem was carried on by Lieutenant Ralph E. Kirsch, (MC)USN (4), who studied the physiological changes of aviators during actual combat flying over enemy-held territory. Changes were found in pulse rate, respiratory rate, blood pressure, axillary perspiration, and palm and skin temperatures just preceding and during the flight over the enemy targets. This investigation indicates the value and feasibility of making studies of the military pilot performing in his normal work environment.

IV. PROCEDURES OF THE INVESTIGATION

The task of studying the pilot in his natural flight environment is not easily accomplished by non-flying personnel. To establish good rapport prior to the securing of data, it was necessary to meet with each flight crew and to explain the purpose and method of the investigation. When the pilots and crew fully understood the reasons behind the investigation, cooperation and assistance were immediately secured. It was evident that the men who fly the aircraft were acutely aware of the need for a study to improve the work place of the pilot.

During the study, the investigators flew two non-stop cross-country flights from Washington, D.C., to Oakland, California, several training flights at Moffett Field, California, and flights into Alaska and the Caribbean area. Observations made during these flights afforded the investigators a general knowledge of flight procedures which are essential in analyzing and interpreting such data. The fact that the investigation was restricted to regularly scheduled flights imposed certain limitations on the use of recording equipment. It had the advantage, however, of insuring "characteristic" conditions of flight which might have been subject to unintentional modification in purely experimental flights simulating routine operation.

Photographs of the pilot's performance were secured by using a Ciné Kodak Special, 16mm. camera, with Super X and Super XX panchromatic film, operated at a speed of 8, 16, or 24 frames per second. This camera is spring driven and runs continously for only 1 1/2 minutes (50 feet) at each winding, when the 16 frames per second speed is used. It is equipped with a 100 ft. magazine thus allowing for photographing only two short sequences of operations before reloading. A wide angle lens was used and photographs were taken at a point approximately 4 to 6 feet to the rear of the cockpit, with and without the use of a tripod. The use of

the tripod and fixed camera was dispensed with early in the study as it proved impracticable for the quick changes in camera position needed to obtain photographs of the pilot's actions.

Since the photographic equipment did not enable the observer to record continuously the operations of the pilot for more than 1 1/2 minutes, it was necessary to supplement cinematographic recordings with observational notes. To accomplish this, the observer used the wire recorder to provide a permanent record of his commentary on the work performed by the pilot and co-pilot during longer periods of flight.

Voice recordings were secured by a General Electric airborne wire recorder, operating at the standard aircraft voltage of 24-28 volts D.C. This apparatus was equipped with special lip microphones and standard voice microphones. The input to the wire recorder came from the intercommunication junction box of the plane, and a second input from a regulation carbon mike which could be keyed into the circuit by the investigator. Headphones connected to the output circuit of the recorder enabled the investigator to hear and select information being recorded.

The airplane most frequently flown was the Navy R5D, a transport airplane. This plane is a four-engined, low-winged monoplane, with a tricycle landing gear. Accommodations are provided for a crew of six: pilot, co-pilot, radio operator, navigator and two relief crew members. The plane is designed to carry either cargo or troops. During the period of investigation, most of the flights were made with only a pilot and co-pilot, but some runs were augmented by a radio operator and a third relief pilot.

Moving pictures and/or voice recordings were taken of the following flight phases: 1) visual inspection of the airplane exterior, 2) cockpit check-off prior to motor starting, 3) motor starting, 4) check-off prior to take-off, 5) take-off and climb, 6) cruise, 7) let-down and landing, and 8) taxiing to line. In addition,

moving pictures were taken of the pilot operating each control separately, starting from the basic flight position (hands on the control column). The latter series of films were taken with the plane on the ground, and with special lighting equipment installed in the cockpit.

A cursory examination of the motion pictures indicated that certain sequences must be subjected to a frame by frame analysis to provide complete information about the use of controls and the time required for their operation. For such an analysis a projection must meet the following requirements:

1. Enlarge image sufficiently to facilitate reading and visual scanning. (approximate size 12" x 12").
2. Provide for reversible operation.
3. Provide for continuous projection of a single frame without burning.
4. Contain a method for counting frames or timing. By counting frames the time element is standardized provided the camera has been run at a constant speed, (1000 frames/min.).
5. Provide a cross grid over the projection screen to facilitate the measuring of distances of various movements.
6. Provide for variable speeds of projection.
7. Provide for centering and focusing the image.

These requirements were met by a modified Moviola projection apparatus.* The modification, which is easily made, consisted of mounting a microswitch to the machine so that an electrical impulse could be obtained for each frame that moved through the projector. By connecting two counters with appropriate switches and batteries into the circuit a running total of the frames viewed could be made at any point in the sequence. If it became necessary to reverse the film, the first counter was shut off and a second counter started. This second counter recorded

*Manufactured by the Moviola Company of Hollywood, California.

the number of frames that the film ran in the reverse direction, thus making it possible to return to the original stopping point and restart the first counter.

Such a procedure insures a high degree of accuracy in determining the performance times of pilot and co-pilot since interpretation and measurements may be repeatedly checked by the same or by a second observer.

V. DISCUSSION OF RESULTS

A. Work Areas

When the casual observer steps into the cockpit of a plane such as the R5D, he is confronted with a maze of instruments and controls. From this apparent confusion of gadgets the pilot is required to select and use various combinations of these instruments and controls during any specific flight phase. Further difficulty is introduced by the fact that there are several models of this plane: R5D-1, -2, -3, and -4, which have slight variations in the cockpit design and arrangement.

For the purpose of studying the location and use of the instruments and controls the cockpit was divided into seven general work areas, (figs. 1-7). The delineation of these areas was based upon the R5D-2 cockpit and with minor changes may apply to other types of airplanes as well.

<u>AREA 1</u>.- Control column, rudder and brake pedals:

The general work area 1 (fig. 1) was selected as the basic flight position in which the pilot is seated with hands on a control column or yoke directly in front of him and his feet on the rudder controls. Most of his movement patterns originate from this position.

The control column consists of a three-quarter wheel open at the top to provide clear vision of the main instrument panel directly in front. The column is moved fore and aft for operation of the main elevator surfaces, and the wheel is turned clockwise or counter-clockwise to operate the ailerons. The other controls mounted on this column are a small switch to operate the mike (on some models this switch is used to operate a small cockpit spotlight), and two fluorescent spot lights which can be focused on the instrument panel. The rudder controls with standard toe-brake attachment are located directly in front of the normal seating positions of the pilot and co-pilot. The rudder surfaces are operated by extension

PILOTS' WORK AREAS

Fig. 1 (Area 1)
Basic Flight Position

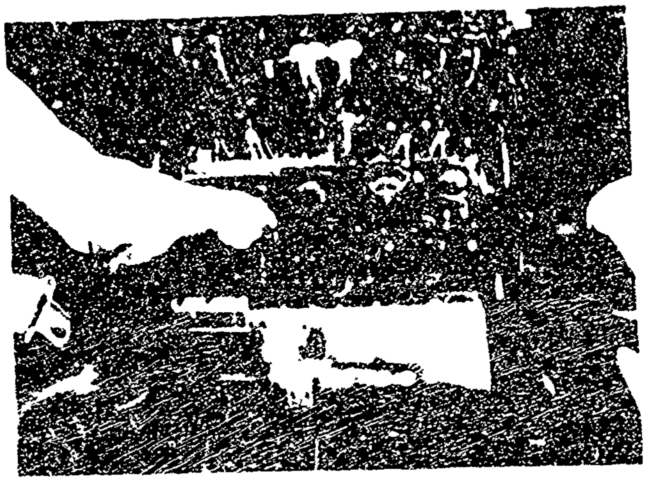

Fig. 2 (Area 2)
Control Pedestal (upper half)

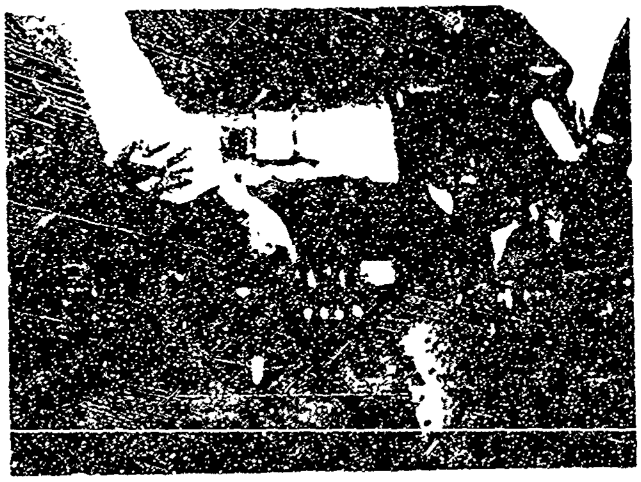

Fig. 3 (Area 3)
Control Pedestal (lower half)

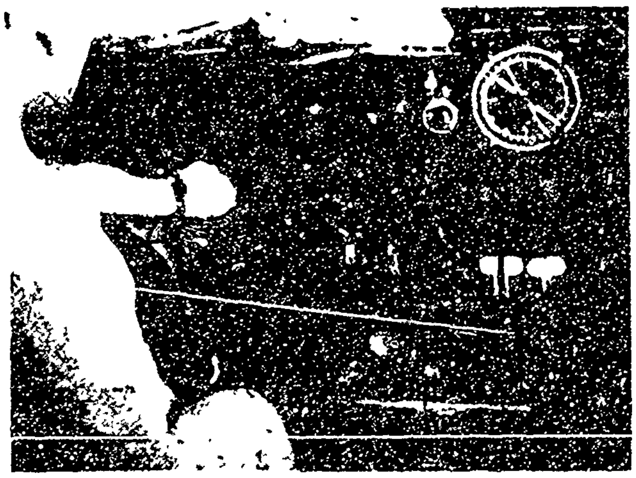

Fig. 4 (Area 4)
Main Instrument Panel

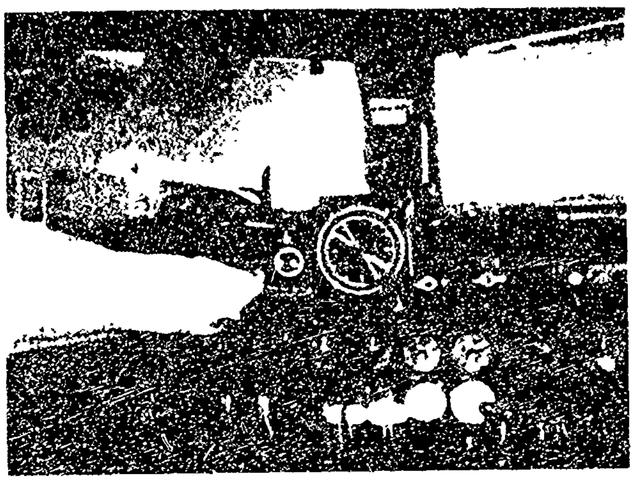

Fig. 5 (Area 5)
Main Instrument Panel (upper portion)
Emergency Controls

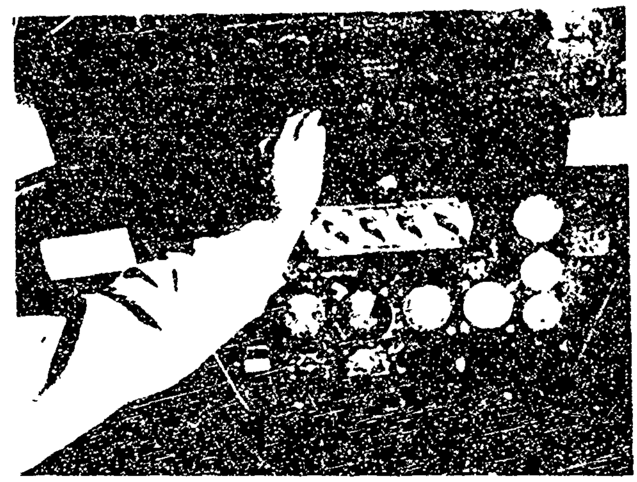

Fig. 6 (Area 6)
Upper Instrument and Switch Panels

Fig. 7 (Area 7)
Side Control Panel

Fig. 8
Typical Pilot and Co-Pilots' Actions
in Areas 2, 3, and 6.

and flexion of the legs, and the brake controls by like action of the feet with the heels resting on the rudder bar.

<u>AREA 2</u>.- Control pedestal (upper half):

The control pedestal is centered on the deck between pilot and co-pilot. Area 2 is composed of the upper half of the control pedestal down to and including the servo control for the automatic pilot (fig. 2). It contains approximately 28 lever type controls moving in the fore and aft plane, 16 knob type controls moving clockwise and counter-clockwise, 6 toggle switches, 4 cranks, and 1 wheel. The controls in this area are located to the side and forward, and at approximately waist level height from the sitting position. They are reached by a basic pattern of movement in which the arm is partially or fully extended forward to the side and slightly downward. Some operations require, in addition, a forward and lateral flexion and rotation of the trunk.

<u>AREA 3</u>.- Control pedestal (lower half):

This area comprises the lower half of the control pedestal (fig. 3). The controls are mostly lever type or toggle switch type moving up or down. There are approximately 17 levers, 3 switches and 1 wheel. These controls require full arm extension downwards at the side with trunk bending to the right.*

<u>AREA 4</u>.- Main instrument panel:

This area (fig. 4) includes that portion of the main instrument panel directly in front of the pilot. The distribution of instruments is such that the basic flight indicators are duplicated — one set directly in front of each pilot — with the manifold pressure, R.P.M., fuel pressure, oil pressure, flap indicator and gear position indicators centrally mounted on the panel in back of the control pedestal. Most of these are indicators which require a visual check but some require an oc-

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*Notations "right" and "left" refer to pilot; co-pilot movements will be in the opposite direction.

casional manual adjustment.

There are 12 knob type controls operated clockwise and counter-clockwise and 3 wheel type controls operated in the horizontal plane. To operate the controls requires a full forward extension of the arm and a partial flexion of the trunk. To reach controls in this area may require considerable deflection of movement around the control column or pedestal.

AREA 5.- Main instrument panel (upper portion):

Area 5 (fig. 5) is located directly above the main instrument panel and extends horizontally along its entire length. It contains the CO_2 fire extinguisher system with warning lights and control handles, and emergency air brake controls at each end of the panel. In the center of the panel is the rudder trim indicator, directly above which is the rudder trim control wheel.

This area has 8 two-finger hook type bars and 2 circular knobs, all operated by straight push or pull action, and a rudder trim control wheel which is operated by right or left turning motion in the horizontal plane. All operations require a full extension of the arm forward at shoulder level with partial flexion of the trunk.

AREA 6.- Pilot's upper instrument and switch panels:

This area is located in the forward center section of the overhead (fig. 6). It contains the electrical switches and indicating instruments and the balance of the engine-operating instruments. Operation of these controls requires a trunk flexion and a forward and upward arm extension. There are 18 rotary knobs and two cranks moving clockwise or counter-clockwise, 48 toggle switches moving up and down, 4 push button type of controls, and 1 knob type control sliding right and left in the horizontal plane. (This last control is peculiar to the R5D-1 model.) The 4 feathering switches are operated by straight push motion.

AREA 7.- Side control panel:

Area 7 is located to the left of the pilot's chair (fig. 7). In this area there are about 10 toggle switches and 1 lever moved up or down and 1 wheel and 4 knobs rotated clockwise or counter-clockwise. Most of these controls are within the normal reach of the left hand when the pilot is in the basic flight position. However, the right hand is occasionally crossed over to operate them, thus requiring trunk flexion and rotation, plus extension of the right arm.

A typical performance of pilot and co-pilot is shown in figure 8. Pilot is working in areas 2 and 3, and co-pilot in area 6. Figure 8a is a film strip showing the complete performance of pilot in operating the rudder trim tab control.

B. Functional Reach Measurements

It has long been recognized that for convenience, quickness and efficiency of operation, the materials or controls that are to be used in any task should be placed in an area within normal functional reach. Figure 9, a schematic drawing by Kosma (5), shows a convenient layout for work areas which has been applied to industrial operations. The diagram suggests that a circular arrangement of work areas is the most efficient. An excellent example of the application of this principle may be seen in the design of organ keyboards and controls, where it is necessary to obtain maximum coordination of both arms and both legs.

Although such working areas have been repeatedly proposed and diagrammed by industrial analysts, the dimensions of the areas are never shown. More recently however, King et al. (6) made maximum reach measurements in the laboratory on a group of Navy pilots seated in a standard Warren MacArthur pilot seat with shoulder straps and lap belt locked. The basic measurements consisted of the horizontal distance from the finger-tips to a reference line running vertically through the midpoint of the intersection between the upper level of the seat cushion and the lower

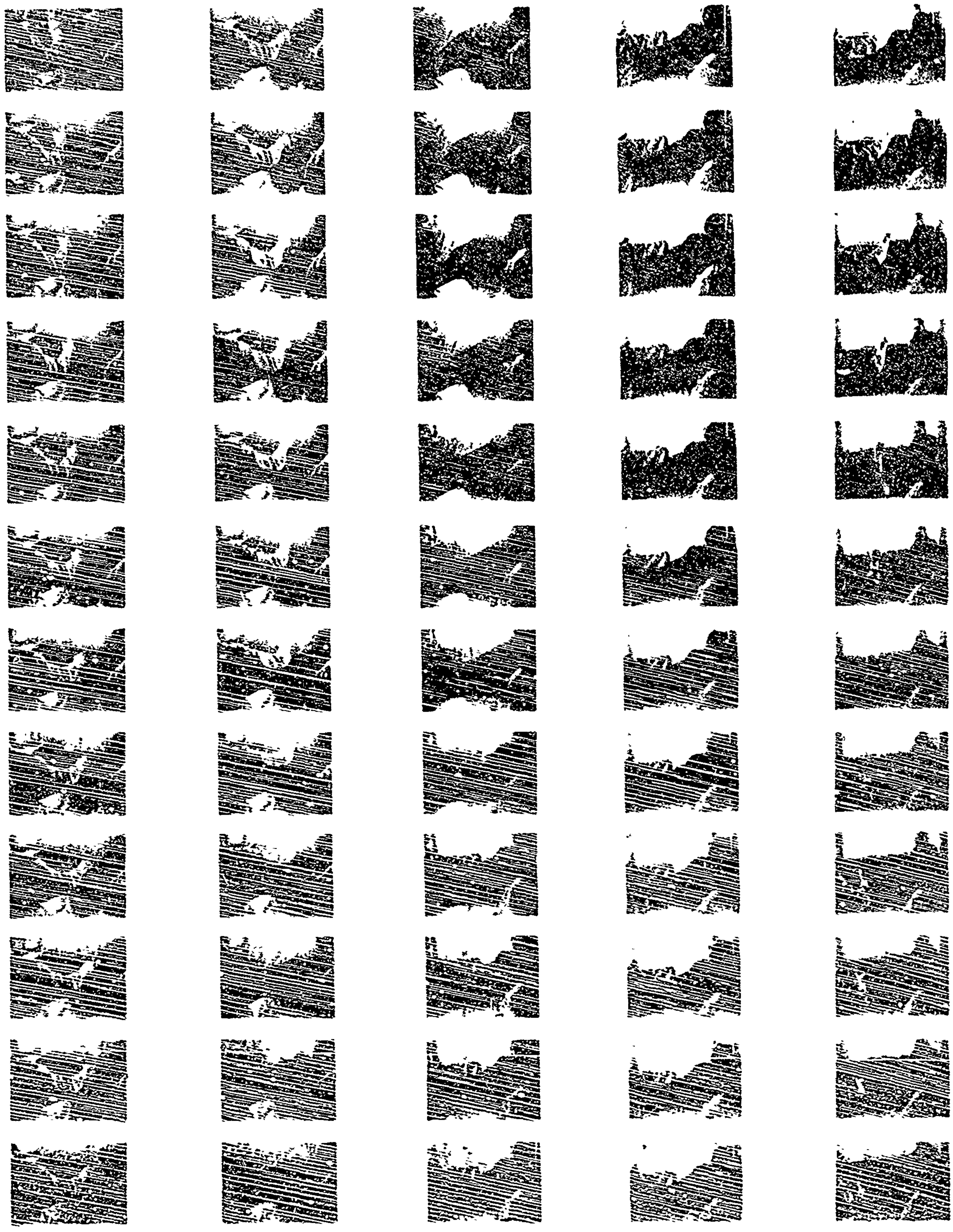

Figure 8a -- Film strip showing pilot operating rudder trim tab control.

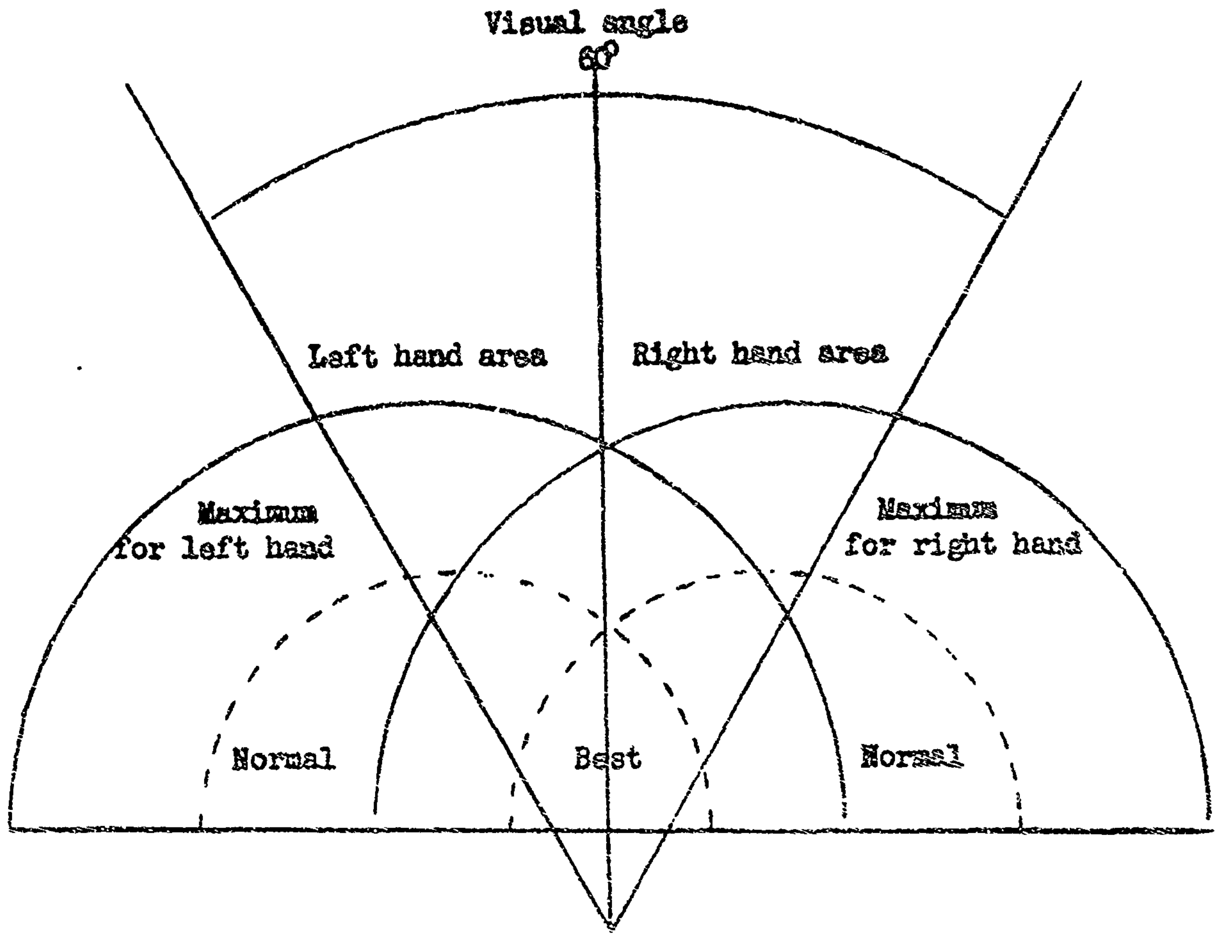

Figure 9. - Circular work-place areas

cushions of the back pad. Maximum reach distances were recorded for 99 points at various heights and angles around the pilot. Data are presented showing reach distances which are maximum for 50% and for 95% of the population studied.

These basic measurements have been applied to the R5D cockpit arrangement, but in doing so consideration had to be given to the adjustment of the pilot's seat. It was found that in the R5D airplane the seat may be raised or lowered 5 inches and moved forward or backward 6 inches to accommodate pilots of various heights. For purposes of comparison it was assumed that the mid-point position of the seat is used by the majority of pilots; thus measurements in the cockpit were taken with the seat in this position. Therefore the maximum correction for extreme positions will be approximately ± 3 inches.

It was not considered practical for the present study to measure the distance

of each control from the reference line established by King. Instead, measurements were taken to the mid-point of each area, and were compared with corresponding measurements developed from his data. Table 1 shows the actual distances to the area mid-points in the R5D, and the corresponding distances which are maximum for 50% and for 95% of King's group.

It can be noticed that only area 7 falls within the maximum reach distances. Areas 2 and 3 are slightly beyond, and areas 4, 5, and 6 are well beyond the maximum distance reached by even 50% of the group. Furthermore not all controls can be operated at these maximum finger-tip distances, since many require various types of hand grasp.

Table 1.- Maximum reach data

Area	Distance required to reach area mid-point	Maximum reach* for 50% of population	Maximum reach* for 95% of population
2	36 inches	32.0 inches	27.5 inches
3	27 "	25.0 "	20.0 "
4	41 "	30.0 "	25.7 "
5	38 "	31.3 "	27.0 "
6	26 "	17.0 "	11.0 "
7	23 "	30.5 "	27.0 "

*Maximum reach distances are measured to finger-tips

Such undesirable discrepancies between maximum reach and required reach are strongly confirmed by observations during flight when the pilot is seen to make extensive body movements. He is often required to bend forward or to the side in order to reach and manipulate the controls. In the following section, the necessity for such body movements will be further demonstrated by an analysis of photographic records.

C. Basic Pilot Movements

"Motion study consists of dividing work into the most fundamental elements possible — studying these elements separately and in relation to one another; and from these studied elements when timed, building methods of least waste." This definition was formulated by the Gilbreths (7) who modified the original work of Taylor (8) and later standardized the fundamental movements into what they called "therbligs".

Various motion and time study engineers have used 17 to 24 therbligs to classify the basic types of movements. These specialists believe that within certain limits the times required to perform a specific basic movement are constant and that the correct motion and the right time to perform any complex operation may be determined by the sum of the times required for the basic movements.

Application of such methods to industry has increased output without imposing additional stress or effort. Expecially is this true where the task is of a highly repetitive nature and where variations from a routine sequence of operations seldom occur.

It would appear that when a task becomes more variable and more highly skilled, and where judgments and interpretations are required, a complete job analysis embodies more than a summation of a group of basic movements. During flight, the reactions of the pilot to the total situation must be considered. The assumption that the job of piloting can be synthesized from a summation of such simple basic movement elements as therbligs is contradictory to the results of many experiments on the acquisition of motor skills.

As the first step in analyzing the pilot's performance in the cockpit, the motion pictures taken of the operation of each control were examined and the movements involved were described in detail. The information obtained is presented in

table 2. Column 1 of this table lists the name of the control. Column 2 gives the work area in which the control is located. Column 3 indicates the type of stimulus which acts as a cue in eliciting the pilot's operation of the control. Four types of cues have been considered:

1. Visual.- This may involve such things as indication on flight instruments (e.g. air speed and turn and bank indicators, altimeter, compass) or cues supplied by the external environment.
2. Auditory.- The sound of the motors may act as cues for operating certain controls; other controls are operated upon verbal command.
3. Kinesthetic and tactile.- The "feel" of the controls or the bodily orientation often provide the cue.
4. Temporal.- Operations may be performed at pre-determined times in a sequence, in which case each operation provides the cue for the next one.

It must be emphasized that the pilot's performance is not a simple matter of responding to a single stimulus, but rather a matter of interpreting the various combinations of cues which he receives, relating them specifically to flight experience, and integrating them into a successful response or series of responses. The pilot is continually required to make judgments and decisions during the flight operations.

Column 4 indicates the classification of the motions of the upper extremities and trunk involved in the operation of each control, according to a commonly used system (9). It is often assumed in time and motion study that the fewer the number of movements, the less amount of energy expended; and the smaller the area of the body that is at work, the less the fatigue that will be experienced. As pointed out by Moore (10), this assumption is not true in all cases. The exception results when small muscle groups are performing at a low degree of efficiency due to supra-optimal loading, or to excessive rates of contraction. It was not the purpose of

Table 2. - Description of pilot's operation of flight controls in the R5D

Col. 1. Control Name	2. Work Area	3. Cues or Stimuli	4. Motion Class	5.* Distance to control and hand used: Pilot	6.* Co-pilot	7. Motion Description
**Control column and wheel	1	1,2,3,4	5	-	-	Extends arms forward, grasps wheel, pushes, pulls and rotates.
**Rudder and brakes	1	1,2,3,4	-	-	-	Extends legs to operate rudder, extends feet to operate brakes.
Throttle friction lock	2	1,4	5	15"R	22"L	Extends arm forward, grasps knob-on-lever with two fingers and thumb, pushes or pulls.
Propeller friction lock	2	1,4	6	20"R	21"L	
**Throttle controls	2	1,2,4	5	12"R	12"L	
**Propeller controls (RPM)	2	1,2,4	6	20"R	19"L	Flexes trunk and arm laterally and forward, grasps knob-on-lever, pushes or pulls. (Sometimes adjusts knob with hand and fingers.)
Tank selector controls	2	1,4	6	12"R	28"L	Flexes trunk, extends arm around center pedestal, grasps knob-on-lever, pushes or pulls.
Cross feed control	2	1,4	6	27"R	19"L	Flexes trunk and extends arm forward and laterally, grasps knob-on-lever, pulls in on knob, raises or lowers lever.
Radio compass control box (frequency selector)	2	1,2,4	5	23"R	18"L	Extends arm, grasps small crank with first and second fingers and thumb, cranks clockwise or counter-clockwise (receiver has three cranks).
Command transmitter	2	1,2,4	5	18"R	25"L	
Command receiver	2	1,2,4	5	17"R	26"L	
**Aileron trim tab	2	1,3,4	6	27"R	26"L	Flexes trunk, extends arm forward and downward, rotates forearm and hand (palm out), grasps wheel mounted vertically, turns wheel by moving arm up and down.
**Elevator trim tab	2	1,3,4	5	13"R	12"L	Extends arm laterally, rests hand on wheel, moves wheel back and forth.
Emergency landing gear extension	2	1,4	6	-	15"L	Flexes trunk laterally, extends arm downward and forward, grasps lever, pulls or pushes.
Recognition lights	2	1,4	5	24"R	25"L	Extends arm laterally and slightly down, grasps toggle-switch in thumb and forefinger, snaps switch up and down.
Servo on-off control (auto-pilot)	2	1,3,4	5	20"R	-	Extends arm down, grips bar with three fingers, pulls up or pushes down.

1.	2.	3.	4	5.	6.	7.
trol (auto-pilot)						pulls up or pushes down.
Supercharger controls (blowers)	3	1,4	6	30"R	24"L	Flexes trunk and extends arm laterally, grasps knob-on-lever, pulls knob out, raises or lowers lever.
Mixture controls	3	1,4	5	30"R	34"L	Extends arm down, grasps knob-on-lever, pulls knob out. raises or lowers lever.
Landing gear control	3	1,2,4	6	33"R	33"L	Flexes trunk, extends arm laterally, downward, grasps knob-on-lever, pushes knob, raises or lowers lever.
Parking brake control	3	1,3,4	6	24"R	-	Flexes trunk and extends arm forward and downward, grasps lever, pulls lever back.
Hydraulic by-pass valve	3	1,4	6	-	36"L	Flexes trunk and extends arm downward to side, inserts two fingers through hole in flap, raises flap.
Wing flap controls	3	1,3,4	5	30"R	28"L	Extends arm laterally and downward, grasps knob-on-lever, moves knob to side, raises or lowers lever.
Cowl flap controls	3	1,4	5	36"R	32"L	Extends arm laterally and downward, grasps knob-on-lever, raises or lowers lever.
Carburetor air filter control	3	1,4	6	26"R	37"L	Flexes trunk laterally, extends arm downward, grasps knob-on-lever, pulls up or pushes down.
Identification radio controls	3	2,4	5	26"R	28"L	Extends arm laterally, grasps toggle-switch, snaps switch up or down.
Gust lock	Near 3	1,4	6	39"R	-	Rotates and bends trunk to side, extends arm downward, grasps pin, pushes away from body.
Clock	4	1,4	6	25"R	-	Extends arm forward, grasps dial knob in thumb and forefinger, pulls or pushes and rotates.
Auto pilot trim adjustments	4	1,4	6	23"R	-	Flexes trunk and extends arm forward, rests hand on notched wheel, moves wheel right or left.
**Altimeter setting	4	1,2,4	6	20"R	20"R	Flexes trunk and extends arm forward, grasps dial in thumb and forefinger, pushes or pulls knob and rotates.
**Directional gyro	4	1,4	6	21"R	22"R	
**Gyro horizon	4	1,4	6	21"R	21"R	
Directional gyro (auto pilot)	4	1,4	6	21"R	-	
Gyro horizon (auto pilot)	4	1,4	6	21"R	-	
Vacuum selector valve	4	1,4	6	-	23"R	Flexes trunk, extends arm forward, grasps dial, rotates.
Manifold gauge selector	4	1,4	6	-	14"R	Flexes trunk and extends arm forward, grasps lever-on-dial, rotates.

1.	2.	3.	4.	5.	6.	7.
**Engine selector valve handle	5	1,4	6	19"R Motors 1,2	18"L Motors 3,4	Flexes trunk, extends arm forward, grasps bar with first and second fingers, pulls.
**CO_2 cylinder valve	5	1	6	13"R	15"R	
**Emergency air brake	5	1,3	6	14"L	16"R	
Rudder trim tab	5	1,3,4	6	21"R	21"L	Flexes trunk and extends arm forward, rests fingers on wheel, moves wheel right or left.
Battery switch	6	1,4	5	36"R	37"L	Extends arm upward, grasps knob, slides knob right or left.
Feathering buttons	6	1,4	5	34"R	33"L	Extends arm upward, pushes button with two extended fingers, or grasps with thumb and two fingers and pulls.
Generator selector	6	1,4	6	-	27"R	Extends trunk and both arms upward, grasps bar dial (selector switch) with one hand, rotates; pushes button (voltammeter) with one extended finger of other hand.
Voltammeter	6	1,4	6	-	27"L	
Warning light dimmer	6	1,4	5	33"R	-	Extends arm upward, grasps dial, rotates.
Ignition switch	6	4	5	31"R	-	
Cabin & cockpit light rheostats	6	1,4	6	34"R	-	Flexes trunk and extends arm upward, grasps dial, rotates.
Prop. anti-icer	6	1,2,4	6	-	33"L	
Wing de-icers	6	1,4	5	39"R	34"L	Extends arm upward, grasps toggle-switch in thumb and forefinger, snaps switch up or down. Some of these switches require also an extension of the trunk.
Fuselage fuel pumps	6	1,4	5	38"R	33"L	
Auxiliary fuel booster pumps	6	1,4	6	41"R	32"L	
Main generator switch	6	1,4	6	-	30"L	
Landing light switch	6	1,4	5	30"R	-	
Pitot heaters	6	1,4	5	25"R	-	
Electric instrument switch	6	1,4	6	32"R	-	
Primer, starter, & mesh switches	6	4	6	32"R Motors 1,2	31"L Motors 3,4	Extends trunk and arm upward, presses momentary contact toggle-switch with one finger.
Command transmitter	6	2,4	5	38"R	40"L	Extends arm upward, grasps small crank in thumb and two fingers, cranks clockwise or counter-clockwise.
VHF transmitter	6	2,4	5	41"R	39"L	
ADF (compass control)	6	4	5	40"R	37"L	

1.	2.	3.	4.	5.	6.	7.
Steering wheel	7	1,4	5	13"L	-	Extends arm forward, laterally and downward, grasps wheel, rotates clockwise or counter-clockwise.
**Filter box radio	7	2,4	5	20"L	23"R	Extends arm to side, grasps toggle-switch, snaps up or down.
**Oxygen regulator	7	1,3,4	6	25"L	25"R	Extends arm downward to side with slight trunk flexion, grasps dial, rotates clockwise or counter-clockwise.
**Windshield defroster	7	1,4	6	27"L	27"R	Extends arm downward with slight trunk flexion, grasps knob, slides knob up or down.

*Where no entry occurs in one of these columns, it indicates that the control is rarely operated by this pilot.

**Indicates that controls are duplicated for co-pilot.

The number of controls in this table will differ from totals expressed previously under area description as only the major ones have been considered. Some minor radio switches etc. have been omitted, and where several controls are operated as a unit they have been counted as one.

this study to make a quantitative estimate of the work involved, but rather to present an analysis of the pilot's movements. For this purpose the following six classifications were used:

1. Finger motion alone
2. Finger and wrist motion.
3. Finger, wrist and forearm motion.
4. Finger, wrist, forearm and upper arm motion.
5. Finger, wrist, forearm, upper arm and shoulder motion.
6. Finger, wrist, forearm, upper arm, shoulder and trunk motion.

The sixth classification is not commonly used in describing the movements of the arm, but was frequently observed in this study.

Columns 5 and 6 list the distance to each control from the basic flight position (hands on yoke) for pilot and co-pilot, and the hand used in its operation. Where a control is usually operated by one of the pilots, the respective space for the other pilot will be left blank. Column 7 describes the sequence of movements required to operate each control starting from the basic flight position.

A summation of these data is presented in Table 3.

Table 3
Summary, by area, of motivating stimuli, movement distances and hand used

		Area 2	3	4	5	6	7	Total
No. of controls in area		14	10	9	4	19	4	60
No. of controls which may be operated in response to:								
Visual stimuli		14	9	9	4	14	3	53
Auditory stimuli		5	2	1	0	3	1	12
Kinesthetic stimuli		3	2	0	2	0	1	8
Temporal sequence		14	10	9	2	19	4	58
Average distance of movement for:	Pilot	19.6	30.4	21.7	16.8	34.9	21.5	
	Co-pilot	20.6	31.5	20.0	17.5	33.3	25.0	
Hand used:	Pilot	13 R	9 R	7 R	3 R 1 L	15 R	4 L	47 R 5 L
	Co-pilot	13 L	8 L	5 R	2 R 2 L	1 R 12 L	3 R	11 R 35 L

Tables 2 and 3 reveal the following information:

Nearly every operation is elicited by visual and/or temporal cues. Auditory and kinesthetic cues are relied upon less frequently, but still to a significant degree. Cues for the operation of a single control may be received through any one of the sensory receptors or the cortex, or by any combination of these sensory (or cortical) impulses. Furthermore, any single receptor is receiving rapid intermittent bursts of stimuli from various instruments or from the environment. Thus the pilot is presented with a highly complex problem of selecting cues requiring responses in the order of their immediate importance.

The overloading of the visual receptors has already been recognized, as evidenced by a previous study (11) in which an attempt was made to develop a system for instrument flying where more use was made of auditory cues. The frequency of use of temporal cues indicates the need for cockpit standardization, training, and simplified procedures of operation. Future development of instruments should be directed towards assisting the pilot to integrate his information without adding to the number of cues he must respond to. This might be accomplished by combining into a single instrument cues which are at present furnished by several.

The distance that the pilot or co-pilot must move his hand from the yoke to reach the controls may vary from 12 inches to 41 inches. Furthermore 57% of the controls require some trunk movement to operate. Some pilots may not choose to operate the more distant controls but may delegate such duties to the co-pilot. This was observed to be a matter of individual preference.

Of the 52 controls which are operated by the pilot, 47, or 90%, require the use of the right hand. For the co-pilot 76% of the 46 controls which he operates require the use of the left hand. This uneven loading is more serious for the co-pilot since in most cases the left is the non-preferred hand. For ease of operation the total load should be distributed as evenly as possible to the various

body members (12). It is evident that the arrangement of controls in the R5D does not provide for an even distribution of load.

The forces required to overcome the resistance in the initial operation of the controls are important considerations (13). The variability of such forces is also related to the sequence in which the controls are operated. Where two controls operated in succession differ greatly in the forces required, there may be considerable overshooting or undershooting of the second adjustment. In this study no data were obtained regarding the forces required to operate the controls. However, the importance of this factor should not be overlooked, and such information should be obtained in future investigations.

D. Flight Phases

In the previous sections the operations of the various controls were described. It is now desirable to consider how these operations are integrated by the pilot and co-pilot during the many standard flight phases. The basic data were taken from the series of motion pictures of the pilot and co-pilot as they performed their duties during the normal flight. Since it was necessary to establish time values, only the films taken at 16 frames per second (960 per minute) were used. For the purpose of analysis, it was assumed that each frame represented .001 minutes, thus introducing a slight constant underestimation of time of about 4%.

Cockpit check-off

Upon entering the cockpit of the R5D, the pilot checks the settings of many of the controls prior to starting the engines. Table 4 lists the controls in the sequence in which they are checked off according to standard NATS procedure, and the work area in which each control is located. In practice it was found that some pilots actually make a physical hand check of all of the listed controls while others do most of it by visual inspection. The normal procedure requires the co-pilot to

Table 4.- Cockpit check-off prior to starting engines

Prescribed NATS Sequence

1. Battery Switch	6	16. Em. Air Pressure	0*
2. Instrument *	6	17. Fuel Gauges	0
3. Wing Tanks	2	18. Oil Gauges	0
4. Carburetor air	3	19. Gyros & Altimeter	4
5. Cross feeds	2	20. Pitot Static Valve	7
6. Brakes, Parking	3	21. Generators	6
7. Propellers	2	22. Fuel Boosters	6
8. Auto pilot	2	23. De-Icers	6
9. Mixtures	3	24. Ignition	6
10. Gear Handles	3	25. Nav. Lights	2
11. Wing flaps	3	26. Land Lights	6
12. Blowers	3	27. Radio check	2,6,7
13. Cowl Flaps	3	28. Inter Phone Check	7
14. Hydraulic By-pass	3	29. Plane Doors	6
15. Emergency Gear extension	2	30. Inter Phone Check List	7

* 0 indicates that the instrument is outside of the pilot's work area and is usually checked by co-pilot.

read off the list, while the pilot makes the actual manual or visual checks. Similar check-off procedures are required during other phases of flight, such as prior to take-off and landing. It was observed during the investigation that these check-off procedures are not always followed, and that even when followed, they are often varied according to the individual pilot's preference.

Table 5 is a process chart based upon cinematographs of the cockpit check-off prior to starting engines. It is drawn according to a time scale and shows the operations in the order performed, the hand used, the work area in which the control is located, and the time required for the operation. A comparison of tables 4 and 5 shows that the operations as actually performed vary somewhat from the standard NATS procedure. The times noted for the checking operations during this particular phase may be expected to vary considerably, depending upon the condition in which the controls are left after securing, servicing or maintenance work.

Figure 10 is a schematic diagram picturing the paths of movement required by the present check-off procedure as prescribed by NATS. The path of movement ori-

TABLE 5. PROCESS CHART

Date: June 15, 1946 **Type of Plane:** R5D **Flight Phase:** Cockpit check-off

Place: Moffett Field, Calif. **Flight Conditions:** Prior to engine starting

PILOT			Time (Minutes)			CO-PILOT		
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
1. Wing tanks								Reads check-off list
2. Carburetor air to position	R	2	.101					Reads
				.10				Reads
3. Cross feed controls	R	2	.062					
				.20				
4. Parking brakes	R	3	.074					
5. Aileron control	R	2	.059	.30				
				.40				
6. Propellers	R	2	.045					
				.50				
7. Auto pilot check	R	3	.025					
				.60				
8. Mixture controls	R	3	.084					
9. Landing gear	R	3	.041	.70				
10. Wing flaps	R	3	.024					
				.80				
11. Supercharger (blowers)	R	3	.068					
				.90				
12. Cowl flaps	R	3	.048					
Unnecessary movement			.043	1.00				
13. Hydraulic by-pass	R	3	.052					
				1.10				
14. Emer gear extension	R	2	.054					
				1.20				
				1.30				
15. Visual inspection of fuel and oil gauge			.115		.115	4	L	Altimeter setting
				1.40				
				1.50				
16. Gyro setting	R	4	.053					
				1.60				
17. Generators	R	6	.049					
				1.70				

TABLE 5. PROCESS CHART (cont'd.)

PILOT			Time (Minutes)			CO-PILOT		
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
18. Observes			.048					
				1.80				
19. De-icers	R	6	.039	1.90				
20. Ignition switches	R	6	.149	2.00				
				2.10				
21. Recognition light	R	2	135	2.20				
22. Warning lights	R	6	.063	2.30				
				2.40				
23. Visual check before starting motor			.206	2.50				
				2.60				

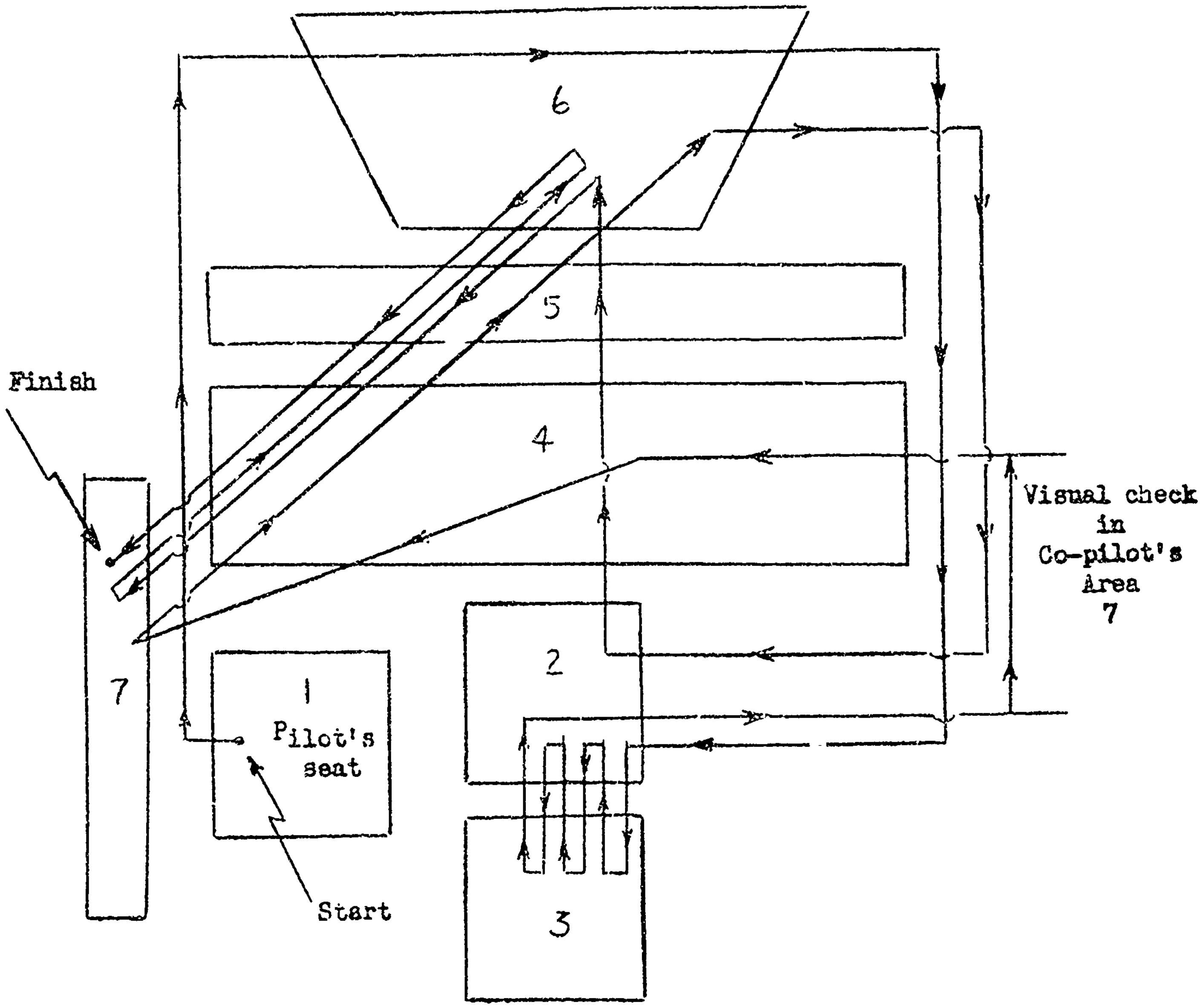

Figure 10. - Paths of movement between work areas during cockpit check-off prior to engine start (NATS procedure)

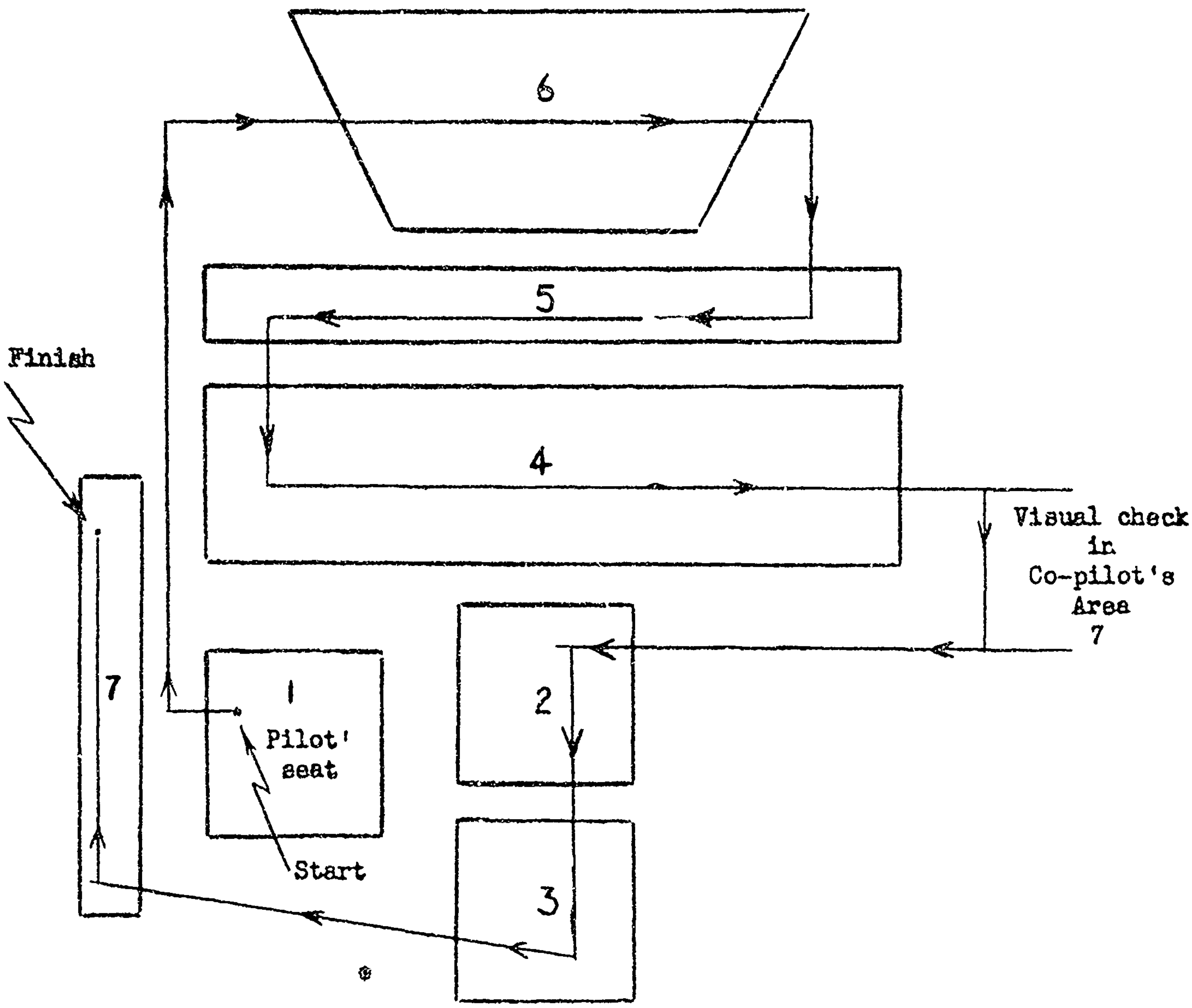

Figure 11. - Paths of movement between work areas during cockpit check-off prior to engine start (suggested procedure)

ginates in area 1 when the pilot raises his hand to operate the battery switch in area 6. The arrows show the pilot's path of movement between the various work areas. It is apparent that there is considerable and needless movement back and forth between areas. Figure 11 shows a simplified path of movement which might be developed by rearranging the order of check-off operations. In this simplified scheme, controls in any one area are completely checked before moving to the next area, thus providing for a more smoothly flowing path of movement. Furthermore, the order of checking controls within each area might be standardized to reduce the likelihood of omissions during the check-off. This presupposes the necessity of maintaining the arrangement of controls as they already exist in the cockpit. In the final analysis, simplifying of operations must be accomplished by modification either of existing sequences of operations or of existing location of controls.

Before recommendations are made for changing the location of controls, further studies of the motion pathways occurring during more critical phases of flight should be undertaken. If operation sequences are found to be standard, aircraft designers may use such information for placement of controls to provide for smooth motion pathways.

Engine start

Table 6 is a process chart of the operations of pilot and co-pilot during the starting of the inboard engine #3 on the co-pilot's side. These operations are repeated for the starting of engine #4, and there is practically no deviation from this pattern. Time factors will vary somewhat depending on the ease with which the engine starts.

In well integrated teams, the pilot will change duties with the co-pilot in starting engines #2 and #1. The change allows the pilot to have more freedom in observing the engines on his side for fire hazard and personnel clearance. If he continued to handle throttle and mixture controls, and the co-pilot the starting

TABLE 6. PROCESS CHART

Date: June 18, 1946 **Type of Plane:** R5D **Flight Phase:** Starting engine

Place: Moffett Field, Calif. **Flight Conditions:** On deck

PILOT								CO-PILOT
			Time (Minutes)					
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
Turns on ignition switch	R	6	.048	.05	.138			Idle Looks out of starboard window
Checks generator switch	R	6	055					
Calls for engine start			.012	.10				
Idle			.105	.15 .20	.083	6	L	Primes engine with first finger
Closes throttle	L	2	.036	.25	.420	6	L	Places first and second finger on mesh and starter switches, presses starter switch
Idle			.390	.30 .35 .40 .45 .50 .55 .60 .65				
Advances throttle and shifts mixture control	L R	2 2	.152	.70	.078	6	L	Presses mesh switch
				.75 .80	.081	6	L	Releases mesh switch
Moves throttle short spurts	L	2	.089	.85				

TABLE 6. PROCESS CHART (cont'd.)

PILOT			Time (Minutes)			CO-PILOT		
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
				.90				
Returns hand to rest position	R.L	1	.183	.95	.315			Idle
				1.00				
				1.05				
				1.10				
				1.15				Shifts hand to switches for engine #4
				1.20				
				1.25				

switches, neither one could readily observe the actual starting of engines #1 and #2.

Take-Off

Tables 7 and 8 are process charts of the pilot's and co-pilot's operations during two normal daytime take-offs. Examination of Table 7 shows that there appears to be a well distributed work load between pilot and co-pilot. The pilot has delegated most of the operation of engine controls to the co-pilot, leaving himself free to control the attitude of the plane. The pilot makes 5 adjustments and the co-pilot 13, and there appears to be sufficient time for both pilots to make their required actions. In contrast, Table 8 indicates that the pilot did not delegate the duties so well. For this take-off the pilot made 25 control adjustments to 19 for the co-pilot.

This variation in distribution of work between pilot and co-pilot indicates that further attempts should be made to standardize take-off procedures. The variation in the total number of movements for each team may or may not be significant since the detailed pattern of movement of a pilot may vary considerably with moderate differences in environmental conditions. The over-all similarity of the sequence of operations during the two-take-offs gives promise for statistical analyses when sufficient data are available.

Landing

The work does not appear to be evenly distributed between pilot and co-pilot during normal straight approach landings (Tables 9 and 10). The pilot is continuously operating throttle, trim tabs and control column. The co-pilot is occupied mainly with adjustments of flap controls, landing gear, and sometimes throttle and propeller, but he appears to be idle for a considerable portion of the time. However, the landing operation is such that it is necessary for one person to integrate

TABLE 7. PROCESS CHART

Date: July 3, 1946 **Type of Plane:** R5D **Flight Phase:** Take-off

Place: Oakland Naval Air Station **Flight Conditions:** Normal daylight take-off

PILOT					CO-PILOT			
			Time (Minutes)					
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
Hand on throttle for advance Left hand on steering wheel	[illegible]	[illegible]	.005					Idle
Moves hand to control column	R	1	.105	.05 .10	.105	2	L	Operates throttle
Places both hands on control column	L, R	1	.432	.15	.012	2	L	[illegible] tension lock directly and locks
				.20 .25 .30 .35	.250	3 3	L L	Reaches for gear handle Holds hand on gear handle
					.010	3	L	Pulls up gear handle
				.40	.020	2	L	Releases tension lock on RPM
				.45	.104	2	L	Makes RPM check
				.50 .55	.048	2	L	Unlocks throttle tension lock
Checks flaps or gears	R	3	.026		.036	2	R	Adjusts throttles
				.60	.024	2	L	Checks throttle tension lock
Returns hand to control column	R	1	340	.65	.100	2	L	Makes RPM adjustment
				70 .75	.070	3	L	Reaches for flap handle
				.80	.040	3	L	Raises flap handle
					.026	3	L	Action completed - returns flap handle to neutral
				.85				

TABLE 7. PROCESS CHART (cont'd.)

PILOT			Time (Minutes)			CO - PILOT		
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
				.90	.097	3	L	Hand leaves flap handle
Adjusts elevator trim	R	2	.044	.95	.014	1	L	Moves hand to arm rest
Moves hand to control column (out of photograph)	R	1	.263	1.00	.076	6	L, R	Starts generator check
				1.05	.006	1	L	Returns left hand to arm rest
					.023	1	R	Returns right hand to arm rest
				1.10 1.15 1.20	.153	6	L	Operates booster-pump switches
Adjusts rudder trim	R	5	.076	1.25	.011	1	L	Returns hand to arm rest
Returns hand to control column	R	1	.145	1.30 1.35 1.40	.188			Listens to radio
Adjusts throttle	R	2	.082	1.45 1.50	.090	6	L	Reaches for something overhead, out of picture
Returns hand to arm rest	R	1	.011		.016	1	L	Returns hand to arm rest

TAKE-OFF COMPLETED

TABLE 8. PROCESS CHART

Date: July 3, 1946 **Type of Plane:** R5D **Flight Phase:** Take-off

Place: Oakland, California **Flight Conditions:** Daylight, routine

PILOT				Time (Minutes)		CO-PILOT		
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	
Advances throttle	R	2	.025		.042			Idle
Steers with left hand	L	1	.063	.05	.020	2	L	Tightens throttle tension
Places hand on yoke	R	1	.018	.10				
Places hand on yoke and moves control column	L L, R	1 1	.176	.15	.238	3	L	Reaches for gear extension handle
				.20				
				.25				
Puts hand on rudder trim tab	R	5	.048					
				.30	.031	3	L	Raises gear handle
*Calls for wheels up			.200	.35	.023	2	L	Releases throttle tension lock
				.40	.048	2	R	Reduces throttle
					.037	2	L	Releases tension lock on RPM
				.45				
Adjusts throttle	R	2	.015	.50	.206	2	R	Decreases RPM to climb setting
Tightens tension lock	R	2	.019					
Moves hand directly to elevator trim	R	2	.050	.55				
Adjusts throttle	R	2	.037	.60				
Adjusts rudder trim	R	5	.038	.65	.022	1	R	Returns to arm rest
Adjusts aileron trim	R	3	.032					
Adjusts throttle	R	2	.061	.70	.082			Idle
*Idle			.030	.75	.024	2	L	Locks tension lock
Adjusts elevator trim	R	2	.032	.80	.050			Idle
Reduces throttle and adjusts tension lock	R	2	.021		.012	2	L	Adjusts RPM tension lock
				.85				

TABLE 8. PROCESS CHART (cont'd.)

PILOT

Sequence of Operations	Hand Used	Work Area	Time (Minutes) Each Operation	Cumulative
Calls for reduction in RPM			.060	90
Adjusts RPM for engines #1,2	R	2	.156	.95 / 100
Adjusts command radio receiver	R	2	.051	1.05 / 1.10
*Idle			.019	
Adjusts aileron	R	3	.038	1.15
Releases throttle tension lock	R	2	.027	1.20
Reduces throttle	R	2	.042	
*Idle			.016	1.25
Adjusts elevator trim	R	2	.019	
Returns hand to wheel	R	1	.047	1.30
Adjusts elevator trim	R	2	.024	1.35
*Idle			.080	1.40
Adjusts elevator trim	R	2	.018	1.45
*Idle			.041	
Adjusts Bendix radio	R	2	.059	1.50 / 1.55
Adjusts throttle	R	2	.035	1.60
Adjusts command radio receiver	R	2	.086	1.65
* During these periods pilot is actually operating control column and rudder				1.70

CO-PILOT

Time (Minutes) Each Operation	Work Area	Hand Used	Sequence of Operations
.026			Idle
.021	2	L	Checks throttle tension lock
.030			Idle
.037	5	L,R	Checks generator
.057			Idle
.061	3	L	Checks hydraulic by-pass valve
.161			Idle
.018	2	L	Locks throttle tension
.025			Idle
.073	2	L,R	Unlocks RPM and adjust RPM with both hands
.010			Idle
.018	2	L	Locks RPM controls
.022			Idle
.265	2	L	Synchronizes motors #3,4

TABLE 9. PROCESS CHART

Date: June 3, 1946 **Type of Plane:** R5D **Flight Phase:** Landing, including part of final approach

Place: Washington, D.C. Flight Conditions: Daylight, routine

Time (Mi[illegible]s)

Cumulative: .05, .10, 15, 20, .25, .30, .35, .40, .45, .50, .55, .60, .65, .70, .75, .80, .85

PILOT

Sequence of Operations	Hand Used	Work Area	Each Operation
Reaches for throttle to reduce power Operates throttle	R	2	334
Returns to control column	R	1	.005
Adjusts elevator trim	R	2	020
Returns to control column	R	1	.003
Reaches for throttle Operates throttle	R	2	.132
Returns hand to arm rest	R	1	.015
Adjusts elevator trim	R	2	072
Returns hand to control column	R	1	.063
Adjusts elevator trim	R	2	.032
Operates throttle	R	2	.060
Returns to control column	R	1	.018
Adjusts elevator trim	R	2	.120

CO-PILOT

Each Operation	Work Area	Hand Used	Sequence of Operations
.110			Idle
.130	3	L	Lowers flap handle
.100	1	L	Returns hand to arm rest
.124			Idle
.031	2	L	Operates throttle tension lock
.030	1	L	Returns hand to arm rest
.032	2	L	Operates RPM tension lock
.028	2	L	Adjusts RPM
.280	1	L	Returns hand to arm rest Idle

TABLE 9. PROCESS CHART (cont'd.)

PILOT			Time (Minutes)			CO-PILOT		
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
				.90	.065	3	L	Turns toward pilot and reaches for gear handle
				.95	.025			Action completed
					.017	3	L	Moves hand to flap control
Returns hand to throttle Operates throttle	R	2	.368	1.00 1.05 1.10 1.15 1.20				Operates flap control Returns to arm rest Idle
Places hand over throttle knobs and grasps all four to hold securely in off position	R	2	.145	1.25 1.30 1.35				
Returns hand to control column	R	1	.095	1.40 1.45				
On the deck-pilot reaches for throttle and holds	R	2		1.50 1.55 1.60 1.65				

Date: June 25, 1946 **Type of Plane**: R5D **Flight Phase**: Landing including part of final approach

Place: Guantanamo **Flight Conditions**: Daylight, routine

Cumulative time scale (Minutes): .05, .10, .15, .20, .25, .30, .35, .40, .45, .50, .55, .60, .65, .70, .75, .80, .85

PILOT

Sequence of Operations	Hand Used	Work Area	Time (Minutes) Each Operation
Hands on throttle	R	2	.031
Returns hand to yoke	R	1	.116
Reaches for throttle and operates throttle	R	2	.440
Adjusts mixture control	R	3	.020
Returns hand to throttle	R	2	.125
Adjusts mixture control	R	3	.003
Returns hand to throttle	R	2	.040
Returns hand to yoke	R	1	.080

CO-PILOT

Time (Minutes) Each Operation	Work Area	Hand Used	Sequence of Operations
.062	1	L,R	Rests arm on arm rest
.121	3	L	Reaches for landing gear
.164	3	L	Pushes gear handle down
.027	3	L	Moves hand to flap lever
.102	3	L	Operates flap handle
.047	1	L	Returns to arm rest
.020	3	L	Adjusts flap handle
.051	1	L	Returns to arm rest
.252	3	L	Adjusts flap

TABLE 10. PROCESS CHART (cont'd.)

PILOT			Time (Minutes)			CO-PILOT		
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
Adjusts throttle	R	2	.080	90	.010	1	L	Returns hand to arm-rest
Returns hand to control column	R	1	.075	95	.075	2	L	Operates his set of throttles
On deck			.027	1.00	.019	1	L	Returns hand to arm rest
Reaches for throttle	R	2			.021	3	L	Reaches for flap handle
				1.05	.062	3	L	Raises flap handle
					.028	1	L	Returns hand to arm rest
				1.10	.012	3	L	Adjusts flap handle
				1.15		1	L	Returns hand to arm-rest

the various sensory cues with the adjustment of controls. This may require quick decision and response on the part of the pilot and there would not be time to delegate these performances to co-pilot.

In both landings charted there appears to be sufficient time for all operations to be easily performed.

Taxi to line following landing

A process chart of the operations of pilot and co-pilot during the taxi to line following landing is presented in Table 11. The pilot steers the plane during most of this period while the co-pilot is concerned with shutting off the motors and making minor control adjustments prior to reading the check-off list.

E. Frequency of use of controls

From the investigator's notes made on the voice recorder, the frequency of use of the various controls was compiled. The voice recorder permitted analysis of sequences of longer duration than could be photographed. Tables 12, 13, and 14 summarize these data for take-off, cruise, and landing respectively, and show the work area in which each control is located, the frequency of its use by pilot and by co-pilot, and the frequency expressed as percent of total operations. For a considerable length of time during take-off and landing the pilot is operating, in addition to the controls listed, the control column and rudder; this will be a highly pertinent factor in formulating "ideal" distribution of work loads between pilot and co-pilot.

The frequency of operation of each control is totalled for four take-offs in Table 12. An average of 9.8 operations were performed by the pilot during each take-off. Most of these were concerned with elevator trim and throttle adjustments and occurred in work area 2. The co-pilot averaged 10.3 operations for each take-off. These consisted mainly of R.P.M. and throttle adjustments in area 2, and wing

TABLE 11. PROCESS CHART

Date: June 1, 1946 **Type of Plane:** R5D **Flight Phase:** Taxi to line following landing

Place: Oakland, Calif. **Flight Conditions:** Daylight, routine

PILOT					CO-PILOT			
			Time (Minutes)					
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
				.05				
Steers plane	L	7	.240	.10	.148	2	L	Cuts motors # 4 and 1
				.15	.055		R	Opens side window
				.20	.069	2	R	Takes off earphones and shuts off radio
				.25				
Idle			.225	.30	.054	2	L	Shuts off motors # 3, 2
				.35	.040	6	L	Reaches overhead for something not shown in picture
				.40	.030	3	L	Raises flap handle
				.45	.039	2	L	Pushes forward throttles for motors # 1 and 4
Holds back throttle on motors # 2, 3	R	2	.102	.50	.083	6	L, R	Raises both hands over head (out of picture)
				.55				
Returns hand to position	R	1	.004					
Idle			.200	.60	.167	3	L	Operates mixture controls
				.65				
				.70				
				.75	.054	2	L	Pushes forward throttles # 2 and 3
Reaches for radio master receiver	R	6	.011					
Idle			.069	.80	.024	2	L	Reaches for something in front of pilot's throttle controls
								Idle
				.85	.015	6	L	Reaches overhead, brings hand down

(47)

TABLE 11. PROCESS CHART (cont'd.)

PILOT			Time (Minutes)					CO-PILOT
Sequence of Operations	Hand Used	Work Area	Each Operation	Cumulative	Each Operation	Work Area	Hand Used	Sequence of Operations
Reaches overhead and turns off switches etc.	R	6	.161	.90				Reads check off list
Not a good picture				.95				
				1.00				
Adjusts mixture control	R	3						
				1.05				

Table 12. - Frequency of Use of Controls during Take-off*

AREA	CONTROL	FREQUENCY OF USE Pilot	Co-Pilot		% OF TOTAL OPERATIONS Pilot	Co-Pilot
2	M.P.	4	10		10.3%	24.4%
	R.P.M.	2	13		5.1	31.7
	Cross feed	1	0		2.6	-
	Auto pilot	2	0		5.1	-
	Elevator trim	11	0		28.2	-
				TOTAL	51.3%	56.1%
3	Mixture control	1	0		2.6	-
	Wheels	2	5		5.1	12.2
	Wing flaps	1	5		2.6	12.2
	Cowl flaps	0	1		-	2.4
	Aileron trim	1	0		2.6	-
	By-pass valve	1	1		2.6	2.4
				TOTAL	15.5%	29.2%
4	Gyro pilot compass	3	0		7.7	-
	" " elevator	1	0		2.6	-
	" " aileron	1	0		2.6	-
	Gyro compass	2	0		5.1	-
				TOTAL	18.0%	0.0%
5	Rudder trim	1	0		2.6	-
				TOTAL	2.6%	0.0%
6	Generators	0	1		-	2.4
	Fuel booster pump	0	4		-	9.8
	Landing lights	1	0		2.6	-
	Green radio	0	1		-	2.4
				TOTAL	2.6%	14.6%
7	Nose wheel	3	0		7.7	-
	Inter-com. switch box	1	0		2.6	-
				TOTAL	10.3%	0.0%
Total operations		39	41		100.3%	99.9%
Average operations per take-off		9.8	10.3			

*Frequencies are totals for four normal daytime take-offs.

Table 13. - Frequency of use of controls by pilot and co-pilot during cruise*

AREA	CONTROL	FREQUENCY OF USE Pilot	FREQUENCY OF USE Co-Pilot		% OF TOTAL OPERATIONS Pilot	% OF TOTAL OPERATIONS Co-Pilot
2	M.P.	4	0		3.3%	- %
	M.P. friction lock	1	0		0.8	-
	R.P.M.	7	0		5.8	-
	Fuel selector valve	3	0		2.5	-
	Cross feed	3	0		2.5	-
	Radio compass (red)	1	0		0.8	-
	Command receiver	21	3		17.4	25.0
	Auto pilot	1	0		0.8	-
	Elevator trim	1	0		0.8	-
				TOTAL	34.7%	25.0%
3	Mixture control	1	0		0.8	-
	Cowl flaps	1	0		0.8	-
	Supercharger	2	0		1.7	-
				TOTAL	3.3%	0.0%
4	Auto pilot compass	22	0		18.2	-
	" " elevator	17	0		14.1	-
	" " aileron	3	0		2.5	-
	Gyro compass	1	0		0.8	-
	Altimeter	1	0		0.8	-
	Clock	1	0		0.8	-
	Scans panel	7	0		5.8	-
				TOTAL	43.0%	0.0%
5	None used	-	-		-	-
6	Generators	0	1		-	8.3
	Landing lights	1	0		0.8	-
	Radio compass (green)	8	4		6.6	33.3
	Booster control pump	2	1		1.7	8.3
				TOTAL	9.1%	49.9%
7	Inter-com. switch box	2	2		1.7	16.7
	Oxygen mask	4	0		3.3	-
	Microphone	3	1		2.5	8.3
	Earphones	3	0		2.5	-
				TOTAL	10.0%	25.0%
Total operations		121	12		100.1%	99.9%
Average operations per 15 min. interval		20.2	2.0			

*Frequencies are totals for six 15 minute intervals of a cruise on auto pilot.

Table 14. - Frequency of use of controls during landing*

AREA	CONTROL	FREQUENCY OF USE Pilot	FREQUENCY OF USE Co-Pilot		% OF TOTAL OPERATIONS Pilot	% OF TOTAL OPERATIONS Co-Pilot
2	M.P.	12	1		34.3%	6.3%
	R.P.M.	2	1		5.7	6.3
	Cross feed	1	0		2.9	-
	Command receiver	1	1		2.9	6.3
	Elevator trim	7	0		20.0	-
				TOTAL	65.8%	18.9%
3	Wheels	0	4		-	25.0
	Cowl flaps	1	0		2.9	-
	Wing flaps	2	7		5.7	43.8
	By-pass valve	1	0		2.9	-
				TOTAL	11.5%	68.8%
4	None used	-	-		-	-
5	Rudder trim	1	0		2.9	-
				TOTAL	2.9%	0.0%
6	Generators	0	1		-	6.3
	Warning bell	1	0		2.9	-
	Landing lights	3	0		8.6	-
				TOTAL	11.5%	6.3%
7	Inter-com. switch box	3	1		8.6	6.3
				TOTAL	8.6%	6.3%
Total operations		35	16		100.3%	100.3%
Average operations per landing		11.7	5.3			

*Frequencies are totals for three landings.

and cowl flaps in area 3. Of the pilot's total operations during take-off, the majority (51.3%) occurred in area 2; similarly, for the co-pilot 56.1% occurred in area 2.

Six 15-minute intervals during cruise were analyzed and the data are totalled in Table 13. The pilot is occupied primarily with adjustments of the auto pilot in area 4 and command radio receiver in area 2. Of his total operations 43.0% occur in area 4 and 34.7% in area 2. The co-pilot operates mainly the radio compass control in area 6 and command radio receiver in area 2; of his total operations 49.9% occur in area 6. The pilot's operations averaged 20.2 as compared with only 2.0 for the co-pilot.

It would appear that under certain cruise conditions the entire work load could be delegated to one of the pilots in order to allow for a period of rest for the other.

Table 14 gives totals based on three landings. Of pilot's operations 65.8% were in area 2 and consisted mostly of throttle and elevator trim adjustments. For the co-pilot, 68.8% of the total operations occurred in area 3, and involved mostly wing flap and landing gear adjustments. The pilot's operations average 11.7 as compared with 5.3 for the co-pilot.

VI. COMMENTS

The results of the present investigation indicate that some of the time and motion principles used in industry can be applied to the analysis of the pilot's task. Motion pictures and voice recordings, with the process charts and frequency-of-use tables derived from them, are convenient ways of obtaining and summarizing objective data concerning this job. Even this preliminary study, designed primarily for evaluation of methods, has produced evidence which indicates that the cockpit design of a current Navy transport plane does not allow for efficient performances. It was found that a large proportion of the controls are beyond the maximum reach of the pilot and that these controls are not grouped so as to permit the smoothest possible movement pathways. There appear to be abnormally high work loads assigned to the pilot's right hand and the co-pilot's left hand, and in certain phases of the flight, work loads are unevenly distributed between the pilot and the co-pilot.

In view of the present findings it is believed that a further application of the procedure would contribute significantly to the design and construction of a better work-place for the pilot. Comparable studies on a large population of pilots operating various types of planes appear to be warranted. Data should be secured under well defined and standardized phases of flight as well as under simulated emergency conditions. The information obtained could then be subjected to statistical analysis to show variability between pilots, flight phases, and planes, and also to provide a basis for determination of common pathways of movement. Such information might provide a sound basis for testing the effectiveness of design in experimental mock-up cockpits prior to actual construction of the plane.

Certain improvements might be made in the photographic equipment and technics employed in future investigations (appendix 1). For example, a fixed camera should be used and be located to the rear, above and between pilot and co-pilot to allow

for an angular shot which would include the performances of both pilots. This might be implemented by a wide-angle lens of approximately 60°. The camera should be driven at a constant speed of 1000 frames per minute. At this speed, a magazine holding 500 feet of 16 mm. film would allow for approximately twenty minutes of continuous recording. Improved lighting of the cockpit is needed if clear photographs are to be obtained under all conditions of flying. The possibility of using infra-red light for night photography should be investigated.

The present investigation has considered mainly the complexity of operation of controls. Major problems may exist in the complexity of the stimuli and the integration of these stimuli in the total performance. Motion pictures of the pilot's operations should be synchronized with those of eye movements, to provide further information regarding the pilot's use of visual cues. Such studies of pilot's eye movements would be a valuable adjunct to the type of data considered in this report for improving training methods, routine operation technics and cockpit design.

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APPENDIX 1

Suggested Outline for Further Study of Pilots' Performances

I. Establish procedure for obtaining photographic records and sound recordings during the basic phases of flight

A. Pre-flight situation
   1. Aircraft inspection
   2. Cockpit check-off
   3. Taxiing procedure
   4. Check-off prior to take-off

B. Flight conditions
   1. Actual take-off
   2. Climb to cruising altitude
   3. Transition from climb to cruise
   4. Cruise
   5. Transition from cruise to let-down
   6. Circuit procedure
      a. Entering traffic circle
      b. Pre-landing check-off
      c. Approach
      d. Landing

C. Post-flight situation
   1. Taxiing to line
   2. Post-flight cockpit check-off
   3. Reports and records

D. Instrument flight conditions (Actual)
   1. Instrument take-off and climb
   2. Beam bracketing or on-course flying
   3. Orientation
   4. Let-down
   5. G. C. A. landing
   6. Instrument Landing System
   7. Flying by radar

E. Military situations
   1. Combat tactics
   2. Carrier landings
   3. Bombing runs
   4. Rendezvous and formation flying, day and night

II. Specifications for experimental conditions

A. Aircraft
   1. Assignment of the more recent types of aircraft for exclusive use in the problem involved

B. Personnel requirements

1. Experienced pilots and co-pilots with instrument ratings
2. Photographer, acquainted with time-motion study technics
3. Radio technician, experienced in all phases of radio communication, radar, etc.
4. Aviation psychologist with flight experience and trained in experimental and/or industrial psychology — preferably both
5. Flight Surgeon with understanding of research technics
6. Laboratory assistants for analysis and summarizing obtained data
7. Various specialists for installation of equipment

C. Equipment

1. Camera for mounting on instrument panel to record eye movements, equipped for synchronization with camera to photograph pilot movements
2. Camera with wide angle lens for photographing entire cockpit (May have to synchronize two for this purpose)
3. Air-borne voice recorder with connections for recording pilot's, co-pilot's, and experimenter's comments
4. Possible use of motion picture sound equipment with boom-type mike located in the center of the cockpit
5. Crystal lip mikes to replace the carbon hand mike

D. Possible use of television equipment

1. Synchronize eye movement and pilot movement on single screen — re-photographing with standard equipment, for analyzing

E. Infra-red photographic methods for photographing night performances

III. Treatment of collected data

A. Motion picture analysis

1. Frame by frame analysis of pilot's and co-pilot's performances to determine operating procedures for all controls
2. Analysis of patterns of movements in the use of combinations of controls
3. Time requirements for use of controls during various flight situations
4. Frequency of use of controls
5. Areas of most frequent use

B. Eye movement analysis

1. Diagram showing eye movements
2. Frequency of use of instruments
3. Time requirements for reading various instruments

C. Voice recordings

1. Inter-relationship of the various team patterns of performance
2. Inter-personnel communication procedures
3. Location of communication problems

IV. Application of technics

A. Single-engine airplanes

B. Jet planes and advanced experimental airplanes

C. Mock-up cockpits of proposed airplanes

V. Application of results to future airplane design

A. Develop general principles for placement of instruments and controls

B. Establish optimum work areas and motion pathways

C. Assist engineers in developing specifications for the flight deck

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Subjecting the pilot's tasks to a job analysis, with its related principles of time and motion by industrial methods, was found to be productive and practicable. Accumulation of quantitative data was of secondary importance, but data obtained in the tests resulted in conclusions concerning layout of instruments as well as improvements for the recording devices. Work areas and relationships to arm reach are discussed, and frequency and manner of performing various flight operations are listed.

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